73-154, by Ott and Wait, limited distribution) and is analogous to the "recovery effect" which has been calculated (Wait and Walters, 1963; Hill and Wait, 1981a) and measured (Millington, 1949) for propagation from land to sea.

The problem of propagating from the clearing to the forest is equally interesting, and the three theories are shown in Figure 6. In this case, both antennas are located 10 m above the ground even with the top of the forest. For short distances, the agreement with the integral equation is not perfect because the numerical distance p as defined by (6) is not large. For distances well beyond the forest transition, the aperture and integral equation theories are in good agreement, but the Tamir (1977) analytic continuation result again is high. Actually for the case of the antennas even with the top of the forest, Tamir's analytic continuation result is independent of the forest parameters.

Other cases for various slab parameters and frequencies have been studied, and the trends are qualitatively similar. In order to use the integral equation approach, we actually replace the abrupt height change from the ground to the forest with a linear transition. This is done automatically by program WAGSLAB so that the terrain slope remains finite. A similar linear height interpolation method has been used in program WAGNER (Ott et al., 1979).

5. EQUIVALENT SLAB PARAMETERS

The program WAGSLAB requires the user to supply the slab parameters along the path. The five slab parameters are as pictured in Figure 1: height (D), horizontal conductivity (σ_h), horizontal relative permittivity (ε_h), vertical conductivity (σ_v), and vertical relative permittivity (ε_v). In the HF band, the wavelength ranges from 10 m to 100 m. Consequently, objects such as trees and buildings are not necessarily electrically small. However, the equivalent slab representation seems to be the only tractable model for forests and urban areas at this time.

In this section, we review the literature and make some recommendations regarding the equivalent parameters for forests, urban areas, and snow cover. It is hoped that future comparisons of theory and measurements for propagation through forests and built-up areas will aid in the determination of the appropriate equivalent parameters. It might turn out that a multilayer slab (Ott and Wait, 1973a; Cavalcante et al., 1982) is more appropriate for modeling forests and built-up areas, but it is felt that our knowledge of the equivalent slab parameters is not precise enough to justify such additional complexity at this time. However, such an extension is possible simply by modifying the surface impedance Δ and the height-gain function G.

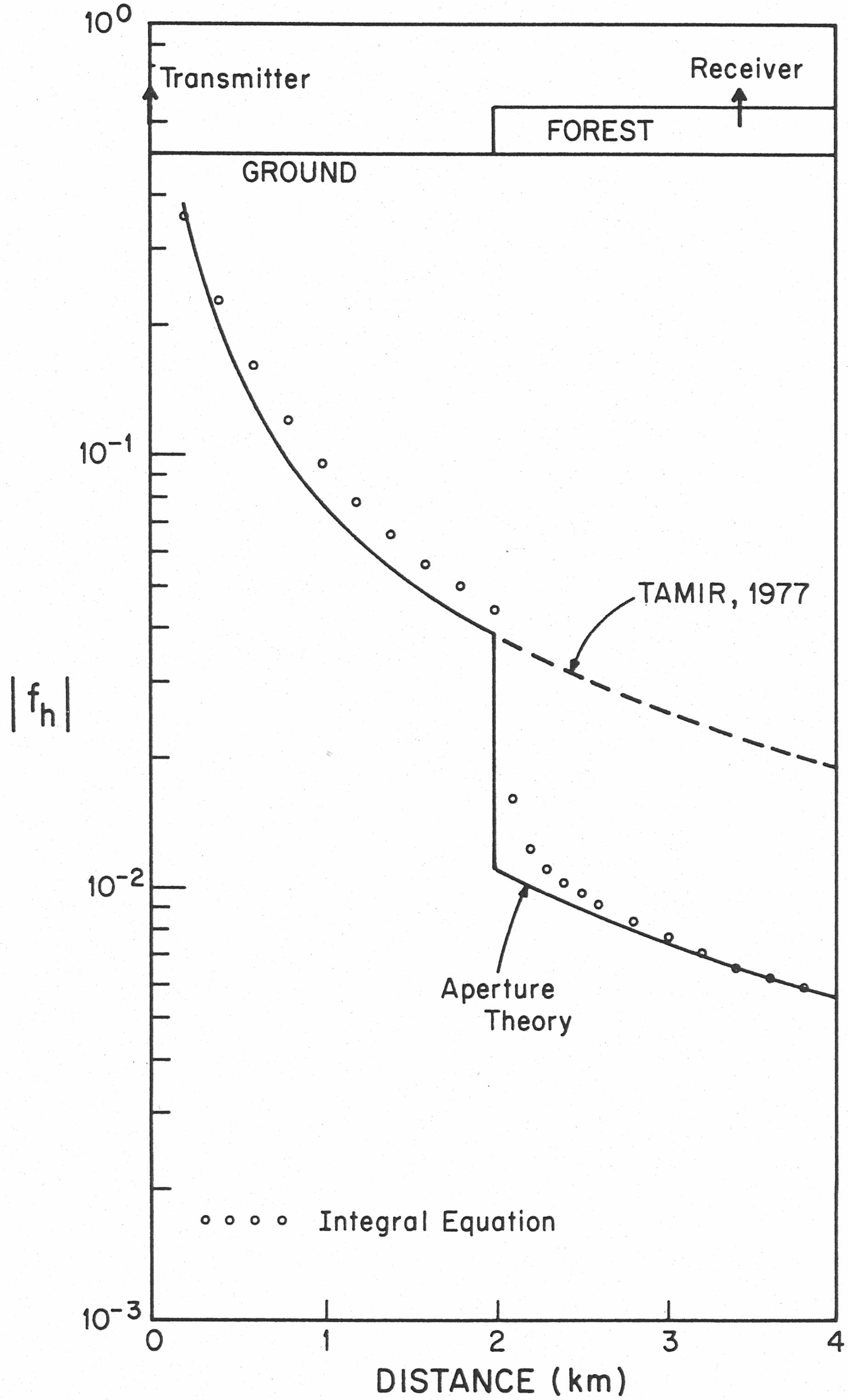

Figure 6. Propagation from a clearing to a forest for a frequency of 10 MHz.

5.1 Forest Cover

During the 1960's there was a great deal of activity in determining the electrical properties of forests in Southeast Asia (Jansky and Bailey, 1966; Parker and Makarabhiromya, 1967). A later workshop (Wait et al., 1974) dealt with many aspects of propagation in forested areas. A general conclusion (Dence and Tamir, 1969) was reached that the equivalent slab model for forests is generally valid for frequencies below about 200 MHz.

Dence and Tamir (1969) refer to three types of forest: "thin," "average," and "dense." The parameters for the slab and the ground for these forest types are given in Table 1. Note that the forest slab is assumed to be isotropic ($\varepsilon_h=\varepsilon_v$ and $\sigma_h=\sigma_v$). The "average" forest is probably most characteristic of Southeast Asia.

A report by the Defense Intelligence Agency (1971) states that the forests of West Germany fall between the "thin" and "average" forests of Dence and Tamir (1969) in Table 1. However, the average tree height is 20 m which corresponds to the "dense" forest of Table 1. Actually the forests of West Germany include both coniferous and deciduous trees, and it seems unlikely that one set of parameters can characterize both types of forests well.

In order to obtain better slab parameters for German forests (or any other forests), two approaches are possible. One is to make ground-wave transmission measurements and to adjust the slab parameters in the theoretical model until a good fit to the measured data is obtained. This is essentially the approach which Causebrook (1978a) used to obtain parameters for the surface impedance of built-up areas in the vicinity of London. A second approach is to attempt to measure the equivalent slab parameters directly (Parker and Hagn, 1966). The first approach has the disadvantage of not yielding any direct information on the slab parameters, but has the advantage of yielding useful transmission results as well as data for fitting slab parameters.

5.2 Built-up Areas

The primary difficulty in characterizing the effect of buildings on HF ground-wave propagation is that the individual buildings are not necessarily small compared to a wavelength. For electrically small hemispherical losses on a perfectly conducting ground, Wait (1959) has shown that an inductive surface impedance results from induced electric and magnetic dipoles in the hemispheres. At MF, Causebrook (1978a) has obtained good agreement between theory and propagation measurements by representing built-up areas by an equivalent surface impedance.

Table 1. Characteristic Parameters of Typical Forests
(Dence and Tamir, 1969)

Parameter		Forest Type		
		"Thin"	"Average"	"Dense"
Tree height	D (m)	5	10	20
Forest	$\varepsilon_v = \varepsilon_h$	1.03	1.1	1.3
	$\sigma_v = \sigma_h$ (S/m)	3×10^{-5}	10^{-4}	3×10^{-4}
Ground	ε_g	5	20	50
	σ_g (S/m)	10^{-3}	10^{-2}	10^{-1}

After attempting a number of approaches which proved to be unsatisfactory at HF, we settled on a fairly simple approach which utilized Causebrook's (1978a) low density theory. We start by taking the low frequency limit of Δ as given by (9). In this case, v_oD is small and we have

$$\tanh (v_oD) \simeq v_oD \quad . \tag{41}$$

Substituting (41) into (9) and keeping only the leading term in v_oD, we have

$$\Delta \simeq \Delta_2 + v_oD\Delta_1 \left(1 - \frac{\Delta_2^{\,2}}{\Delta_1^{\,2}}\right) \quad . \tag{42}$$

For most cases, $|\Delta_2|$ will be much less than $|\Delta_1|$ at low frequencies, and the last term in (42) can be neglected to give the final result

$$\begin{aligned} \Delta &\simeq \Delta_2 + v_o\, D\Delta_1 \\ &= \Delta_2 + ikD \left(1 - \frac{1}{\varepsilon_{vc}}\right). \end{aligned} \tag{43}$$

Causebrook's (1978a) low density theory gives the following result:

$$\Delta \simeq \Delta(0) + ikD \left[1 - \frac{\ln(1 + 10\ B)}{10\ B}\right] \ , \tag{44}$$

where B is the fractional building coverage of the ground and $\Delta(0)$ is the impedance at the surface of the ground. Thus we can equate Δ_2 to $\Delta(0)$. The second terms in (43) and (44) can then be equated to yield the following expression for ε_{vc}:

$$\varepsilon_{vc} = \frac{10\ B}{\ln(1 + 10\ B)} \quad . \tag{45}$$

Since B is real and positive and less than one, (45) can be satisfied by the following:

$$\varepsilon_v = \frac{10\ B}{\ln(1 + 10\ B)} \text{ and } \sigma_v = 0 \quad . \tag{46}$$

As the building density B approaches zero, ε_v approaches unity as it should for free space. A plot of ε_v as a function of B is given in Figure 7. Strictly speaking, B should be limited to values much less than unity since (46) was derived on the basis of low density. Although the previous result provides no information on the horizontal parameters of the slab, ε_h and σ_h, it seems reasonable to equate them to the vertical parameters on the assumption of roughly cubic buildings. Thus the final result for the slab parameters is

$$\varepsilon_v = \varepsilon_h = \frac{10\ B}{\ln(1 + 10\ B)} \tag{47}$$

and

$$\sigma_v = \sigma_h = 0 \quad .$$

For cases where built-up areas are mixed with forest, it seems reasonable to increase ε_v, ε_h, σ_v, and σ_h by the appropriate forest values. Also, even though the result in (47) is derived by matching the slab impedance to Causebrook's (1978a) result in the low frequency (small kD) limit, we assume that the slab parameters are frequency independent. This will mean that when kD is no longer small Δ will be different from Causebrook's (1978a) result in (44). However, since we have converted Causebrook's result into equivalent slab parameters, we no longer have the restriction of small kD. Thus we can use (47) at HF. However, improvements in (47) can probably be made once we have propagation measurements through built-up areas at HF.

5.3 Snow Cover

The electrical properties of snow and ice have been reviewed by Evans (1965). For dry snow, the dielectric constant of snow varies almost linearly with density

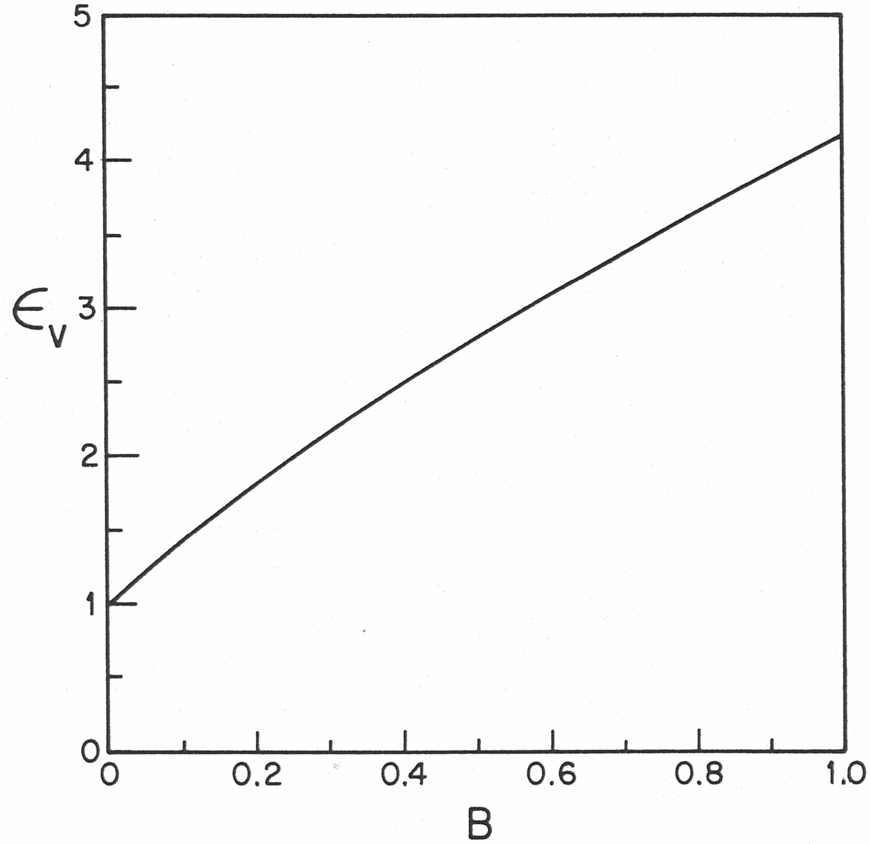

Figure 7. Relative permittivity ε_v versus building density B.

from a value of unity for free space to approximately 3 at the density of ice. The conductivity of dry snow is very small.

The presence of liquid water in snow can raise both the dielectric constant and the conductivity dramatically (Evans, 1965). At a frequency of 1 MHz, Von Hippel (1954) has measured a dielectric constant of 1.2 and a conductivity of 1.85×10^{-6} S/m for freshly fallen snow and a dielectric constant of 1.55 and a conductivity of 2.5×10^{-5} S/m for hard-packed snow followed by light rain. No anisotropy is noted for snow by Evans (1965) or Von Hippel (1954).

To illustrate the effect of snow accumulation on propagation, we show the change in surface impedance as a function of frequency in Table 2. We take the larger value of permittivity for hard-packed, wet snow in order to show the largest effect which is likely for a given snow depth. Although the assumption of a frequency independent conductivity is not correct, the loss tangent for snow is so small that the error in conductivity is unimportant. As seen in Table 1, the effect of increasing snow depth is to increase both the magnitude and phase of Δ, but not greatly. As seen by the flat-earth result in (6), an increase in $|\Delta|$ will result in a decrease in field strength. In Figure 8 we illustrate the effect for a spherical earth. The curves in Figure 8 were computed by a numerically efficient

Table 2. Magnitude and Phase of Surface Impedance Δ as a Function of Snow Depth D. Parameters:
$\varepsilon_v = \varepsilon_h = 1.55$, $\sigma_v = \sigma_h = 2.5 \times 10^{-5}$ S/m,
$\varepsilon_g = 10$, $\sigma_g = 10^{-2}$ S/m

Frequency \ D	0	0.5 m	1.0 m
3 MHz	$0.128 \angle 39.8°$	$0.138 \angle 42.6°$	$0.147 \angle 45.1°$
10 MHz	$0.218 \angle 29.2°$	$0.244 \angle 34.9°$	$0.274 \angle 39.3°$
30 MHz	$0.282 \angle 14.1°$	$0.338 \angle 25.5°$	$0.427 \angle 30.8°$

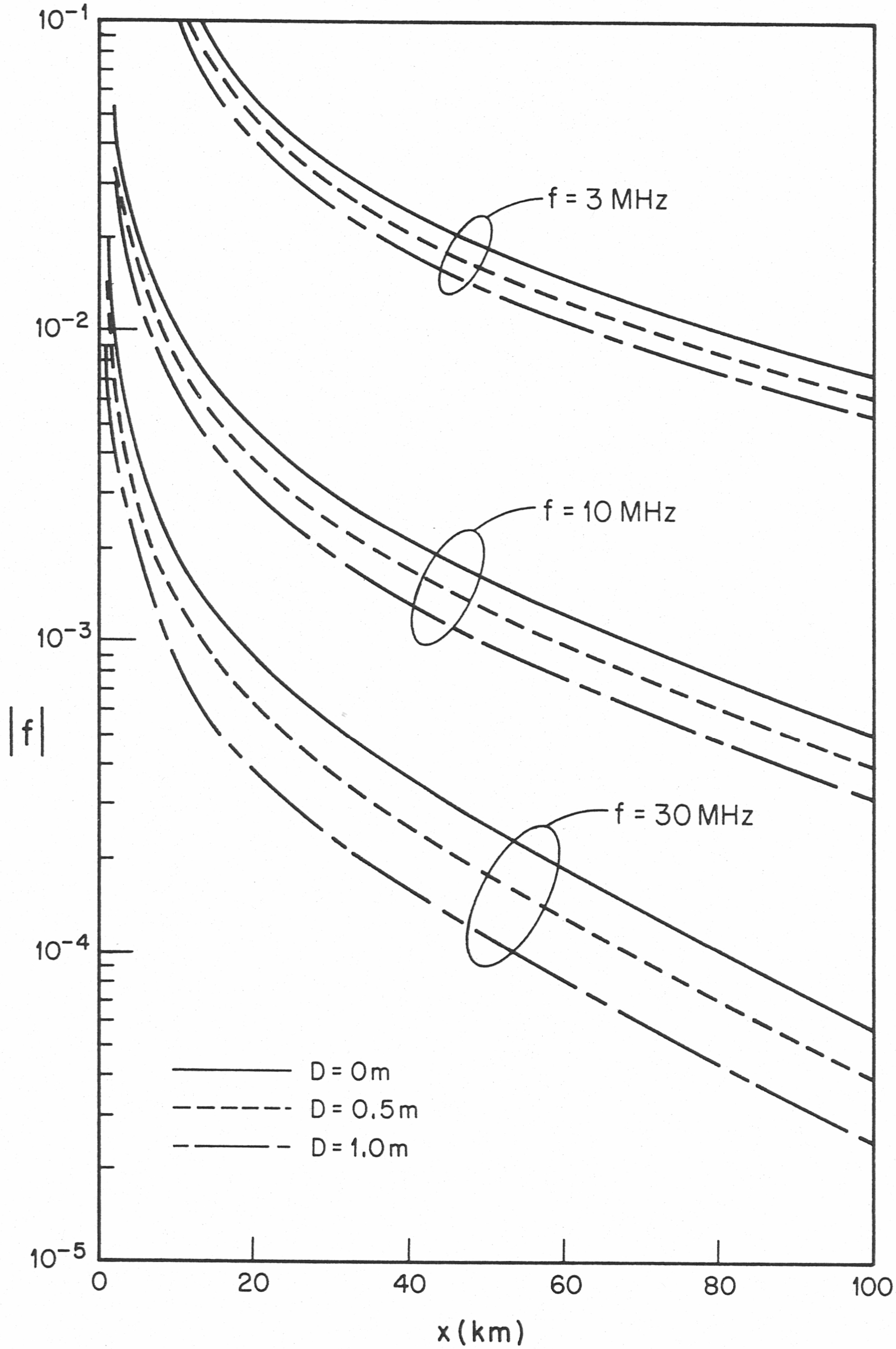

Figure 8. Magnitude of the spherical earth attenuation function as a function of frequency and snow depth D. Parameters: $\varepsilon_v = \varepsilon_h = 1.55$, $\sigma_v = \sigma_h = 2.5 \times 10^{-5}$ S/m, $\varepsilon_g = 10$, $\sigma_g = 10^{-2}$ S/m.

method (Hill and Wait, 1980) which has been used for calculations of ground-wave propagation over sea ice (Hill and Wait, 1981b).

In the case of HF ground-wave propagation over sea ice, a trapped surface wave (Hill and Wait, 1981b) was supported because of the highly inductive surface impedance. As seen in Table 2, a layer of snow over ground does not produce a phase angle of Δ much larger than 45°. Consequently, the main effect of the snow layer is to increase the magnitude of Δ and to decrease the ground-wave field strength. For small depths the effect is small, but for depths of packed snow on the order of a meter the effect becomes significant. As seen in Figure 8, the effect is more prominent at the higher frequencies.

6. SPECIFIC PATH CALCULATIONS

In this section we apply program WAGSLAB to several paths. The smooth paths in the Netherlands are a good check on WAGSLAB because the exact residue series solution for a spherical earth (Hill and Wait, 1980) is available as a check. Both earth curvature and atmospheric refraction are included in WAGSLAB by inputting the appropriate earth radius. In all cases, we used the 4/3 earth radius value ($a \simeq 8500$ km) to account for normal atmospheric refraction (Bremmer, 1949; Wait, 1962), but other values could be used for different atmospheric conditions.

The irregular, forested terrain in southern West Germany presents a greater challenge to the integral equation approach. We have no experimental results as checks for these paths, but reciprocity provides a good theoretical check. Also, we have found that the multiple knife-edge model of Vogler (1981) is in reasonably good agreement with the integral equation solution for long, rough paths.

6.1 Smooth Paths in the Netherlands

Measurements of field strength and bit error rate have recently been carried out on paths of 60 km and 80 km in the Netherlands (Van der Vis, 1979). The frequencies range from 2 MHz to 30 MHz, and both vertical and horizontal polarization were transmitted and received. Both paths had the same transmitter, and the two paths were nearly in line. An examination of topographic maps of the area revealed that both paths were over very smooth (less than a few meters in elevation change), unforested terrain with no cities. The main feature of interest was a section of low ground conductivity (dry, sandy soil) at the end of the 80 km path. Consequently, we modeled the path with two smooth sections as shown in Figure 9. Unfortunately, no ground conductivity measurements were made, but we assume the values suggested by Van der Vis (1979): $\epsilon_g=15$ and $\sigma_g=10^{-2}$ S/m for the first